Quick introduction to Quarkonium-Production Phenomenology

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Part I

Introducing heavy-quarks

Note : most of open HF materials from Ingo Schiebein's slides

Heavy quarks: Definition

Quarks heavy :⇔ $m_h \gg \Lambda_{\rm QCD} \sim 250$ MeV

- $m_h \gg \Lambda_{\rm QCD} \Rightarrow \alpha_s(m_h^2) \propto \ln^{-1}\left(\frac{m_h^2}{\Lambda^2_{\rm QCD}}\right) \ll 1$ (asymptotic freedom)
- m_h sets hard scale; acts as long distance cut-off

charm:	$m_c \sim 1.5$ GeV	$\Lambda_{\rm QCD}/m_c \sim 0.17$	$\alpha_s(m_c^2) \sim 0.34$
bottom:	$m_b \sim 5$ GeV	$\Lambda_{\rm QCD}/m_b \sim 0.05$	$\alpha_s(m_b^2) \sim 0.21$
top:	$m_t \sim 175$ GeV	$\Lambda_{\rm QCD}/m_t \sim 0.001$	$\alpha_s(m_t^2) \sim 0.11$

⇒ Perturbation Theory (pQCD) applicable!

- The smaller the ratio $\Lambda_{\rm QCD}/m_h$, the smaller effects of non-perturbative QCD (such as hadronization)
- Top quark decays before it could hadronize due to its large mass ($\Gamma \propto m_t^3$):
  $\Gamma \simeq \Gamma(t \to bW) \simeq \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2 \simeq 1.76 \text{ GeV } \left(\frac{m_t}{175 \text{ GeV}}\right)^3$

Heavy quarks: Why?

Extensively studied at e^+e^-, photon–hadron, and hadron–hadron colliders. Why?

Many topics (production and decay of heavy quarks):

- Tests of pQCD
  - Factorization, PDFs, FFs, resummations, higher order calculations
  - $g + g \to b + \bar{b}$: gluon PDF
  - $g + s \to W + c$: strange PDF; $g + c \to \gamma + c$: charm PDF
- Important for new physics
  - Understand production of known heavy objects to find new heavy objects
  - New physics often couples to heavy states
  - Higgs boson discovery
  - Background to new physics
- CKM matrix, $B - \bar{B}$ mixing, CP violation
- Measurement of the spin (top decays before hadronization and the products retain all spin correlations)
- Probe of deconfinement: produced at the early stages of an heavy-ion collision (no thermal production)

Open and closed heavy flavour production: Definitions

- Top quarks: decay before hadronization → Not considered here.
- Charm and bottom quarks: hadronize into
  - c and b hadrons: D, B, Λ_c, ...(→ open heavy flavour) ($+B_c$)
  - $c\bar{c}$ and $b\bar{b}$ bound states: quarkonia
- Among the quarkonia the vector mesons J/ψ, Υ, ..., are unique since they decay into a di-muon a few percents of the time. This is extremely useful to detect them in an heavy-ion collision.
- Quarkonia do not exhibit explicit charm and beauty quantum numbers (sometimes called closed HF)

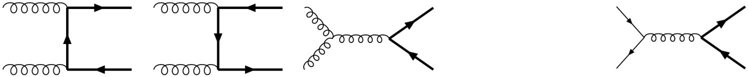
Part II

Heavy-quark/flavour production

Heavy quark hadroproduction at leading order (LO)

Leading order subprocesses:

1. $gg \to Q\bar{Q}$
2. $q\bar{q} \to Q\bar{Q} \quad (q = u, d, s)$



- The gg-channel is dominant at the LHC ($\sim$ 85% at $\sqrt{S} = 14$ TeV).
- The total production cross section for heavy quarks is finite.
  The minimum virtuality of the t-channel propagator is m^2. Sets the scale in α_s.
  Perturbation theory should be reliable.
- Note: For $m^2 \to 0$ total cross section would diverge.

See M. Mangano, hep-ph/9711337; Textbook by Ellis, Stirling and Webber

One loop QCD corrections: next-to-leading order (NLO)

Next-to-leading order (NLO) subprocesses:

1. $gg \to Q\bar{Q}g$
2. $q\bar{q} \to Q\bar{Q}g \quad (q = u, d, s)$
3. $gq \to Q\bar{Q}q, g\bar{q} \to Q\bar{Q}\bar{q}$ [new at NLO]
4. Virtual corrections to $gg \to Q\bar{Q}$ and $q\bar{q} \to Q\bar{Q}$

NLO corrections for $\sigma_{\rm tot}$ and differential cross sections $d\sigma/dp_T dy$ known since long:

- Nason, Dawson, Ellis, NPB303(1988)607; Beenakker, Kuif, van Neerven, Smith, PRD40(1989)54 [$\sigma_{\rm tot}$]
- NDE, NPB327(1989)49; (E)B335(1990)260; Beenakker *et al.*,NPB351(1991)507 [$d\sigma/dp_T dy$]

Well tested by recalculations and zero-mass limit:

- Bojak, Stratmann, PRD67(2003)034010 [$d\sigma/dp_T dy$ (un)polarized]
- Kniehl, Kramer, Spiesberger, IS, PRD71(2005)014018 [$m \to 0$ limit of diff. x-sec]
- Czakon, Mitov, NPB824(2010)111 [$\sigma_{\rm tot}$, fully analytic]

Next-to-next-to-leading order, i.e. at two loops

Channels: $q\bar{q}$, gg, qg

- Two-loop virtual most difficult $M_2^{(0)} + M_2^{(1)} + M_2^{(2)}$
  - Analytic approach: Bonciani, Ferroglia, Gehrmann, Maitre, Studerus, von Manteuffel ('08-'10)
  - Numeric approach: Czakon, Mitov et al.
- Virtual + Real $M_3^{(0)} + M_3^{(1)}$
  Dittmaier, Uwer, Weinzierl ('08)
- Subtraction method for IR singularities in double real $M_4^{(0)}$
  Czakon ('10-'11)
- Available now for top pair production!
- Total cross section Czakon, Mitov, PRL110(2013)252004
- Differential distributions Czakon, Mitov, arXiv:1411.3007
- Analytic approach not yet complete
  [Bonciani et al.]

NB: Some statements should be updated !

Very large scale uncertainties at NLO in c,b production

NNLO will be crucial to make progress!

Heavy flavor schemes

Requirements:

(1) $\mu \ll m$: Decoupling of heavy degrees of freedom

(2) $\mu \gg m$: IR-safety

(3) $\mu \sim m$: Correct threshold behavior

Problem:

- Multiple hard scales: m_c, m_b, m_t, μ
- Mass-independent factorization/renormalization schemes like $\overline{\text{MS}}$
- A single $\overline{\text{MS}}$ scheme cannot meet requirements (1) and (3) (is unphysical).

Way out: Patchwork of $\overline{\text{MS}}$ schemes S^{n_f,n_R}

- Variable Flavor-Number Scheme (VFNS): $S^{3,3} \to S^{4,4} \to S^{5,5}$
- Fixed Flavor-Number Scheme (FFNS): $S^{3,3} \to S^{3,4} \to S^{3,5}$ (3-FFNS)
- **Masses reintroduced** by backdoor: threshold corrections (=matching conditions)

Factorization for 1-particle inclusive reactions $A + B \to H + X$

$A + B \to H + X$: $\quad d\sigma = \sum_{i,j,k} f_i^A(x_1) \otimes f_j^B(x_2) \otimes d\sigma(ij \to kX) \otimes D_k^H(z)$

sum over all possible subprocesses $i + j \to k + X$

Parton distribution functions:
$f_i^A(x_1, \mu_F), f_j^B(x_2, \mu_F)$
non-perturbative input
long distance
universal

Hard scattering
cross section:
$d\sigma(\mu_F, \mu'_F, \alpha_s(\mu_R), [\frac{m_h}{p_T}])$
perturbatively computable
short distance
(coefficient functions)

Fragmentation functions:
$D_k^H(z, [\mu'_F])$
non-perturbative input
long distance
universal

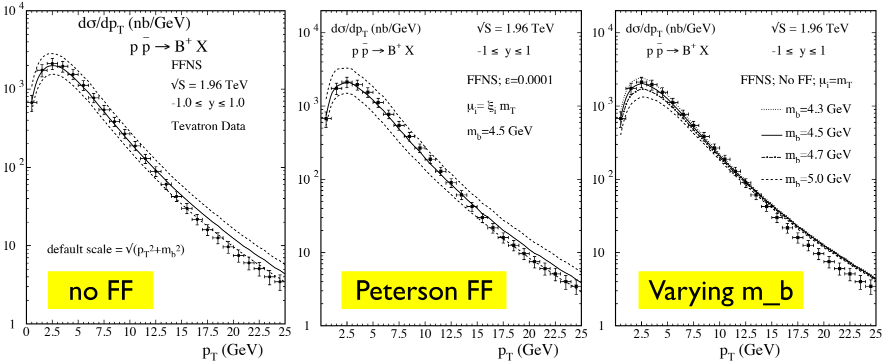
Accuracy:

light hadrons: $\mathcal{O}((\Lambda/p_T)^p)$ with p_T hard scale, Λ hadronic scale, $p = 1, 2$
heavy hadrons: if m_h is neglected in $d\sigma$: $\mathcal{O}((m_h/p_T)^p)$

Details (subprocesses, PDFs, FFs; mass terms) depend on
the Heavy Flavour Scheme

First comparison with data

NLO FFNS works very well for pT up to roughly 5m



GM-VFNS: General Mass - Variable Flavour Number Scheme

- FFs in x-space in the BKK approach
- Heavy-quark initiated contributions ($Q+g \rightarrow Q+X$, ...) get very large at small p_T in the massless case:

  (i) switch off heavy-quark PDF sufficiently quickly
  OR
  (ii) calculate these subprocesses with mass
- Error bands: μ_R , μ_F , μ_F' varied independently
- Predictions for D and B prod. at Tevatron, RHIC, LHC:
  arXiv:1502.01001, 1202.0439, 1109.2472, 0901.4130, 0705.4392, hep-ph/0508129, ph/0502194, ph/0410289
- Predictions including D-decay and B-decay:
  arXiv: 1310.2924, 1212.4356

FONLL : Fixed Order Next-to-leading log.

- FFs in N-space in the PFF approach
- RS-FOM0 gets very large at small p_T:

  $G(m,p_T) = p_T^2/(p_T^2 + a^2\ m^2)$ with **a=5**

  needed to suppress this contribution sufficiently rapidly
- Central scale choice for FO, RS, FOM0: m_T
- Error bands: $\mu_F = \mu_F$' (only two scales varied)
- Predictions for LHC7 in arXiv:1205.6344

Monte Carlo & Event Generators

- MC@NLO, POWHEG: hep-ph/0305252, arXiv:0707.3088
  consistent matching of NLO matrix elements with parton showers (PS)

- Flexible simulation of hadronic final state
  (PS, hadronization, detector effects)

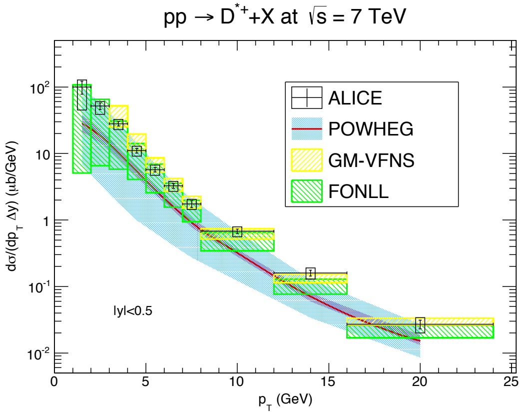
  Note: FONLL and GM-VFNS only one-particle inclusive observables

- High accuracy: NLO+LL*
  (FONLL and GM-VFNS have NLO+NLL accuracy)

- Simulation of hadronic final state involves tuning;
  NOT a pure theory prediction!

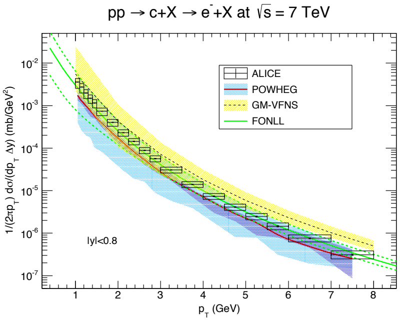
Comparison for meson production

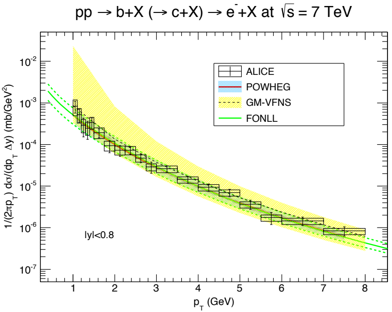
arXiv:1405.3083



Comparison for leptons from heavy-flavour decays

arXiv:1405.3083





Part III

Introducing quarkonium

The discovery of heavy quarks: the quarks become real !

The November revolution (in 1974) more than 40 years ago !

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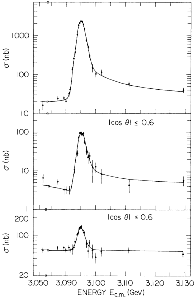

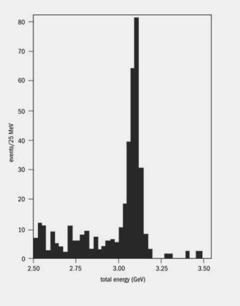

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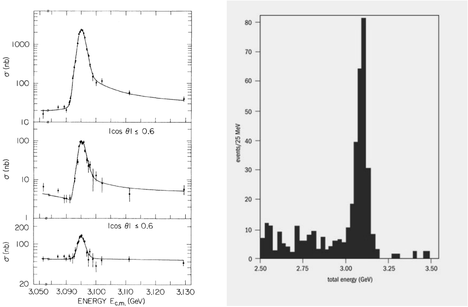

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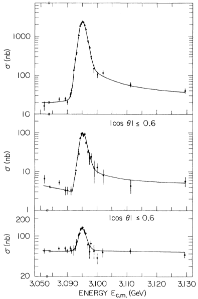

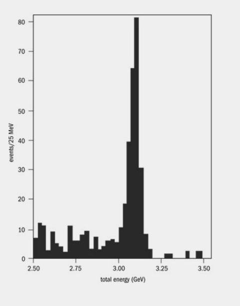

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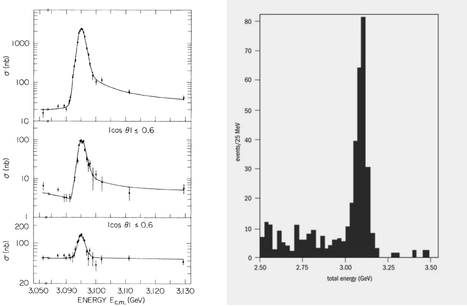

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- Additional heavier resonances were subsequently discovered

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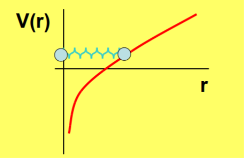

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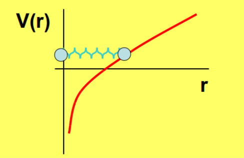

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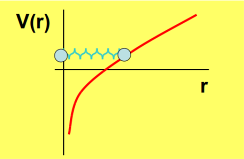

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 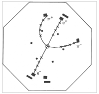

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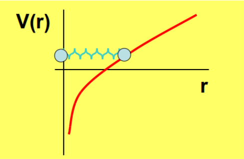

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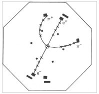

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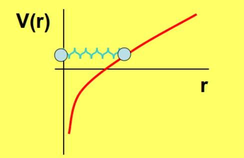

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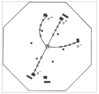
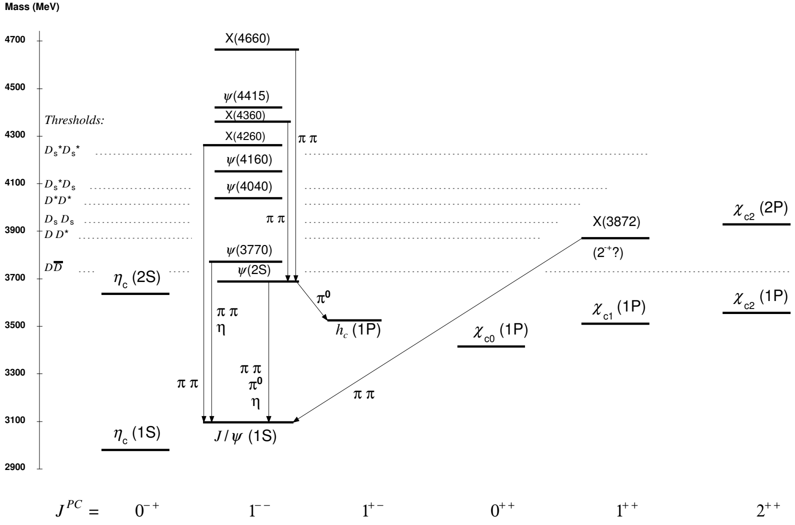


- The quarks acquire a physical existence !
- B. Richter (SLAC) and S. Ting (BNL) got the Nobel prize in 1976

The Quarkonium ($Q\bar{Q}$) families

- Two families:



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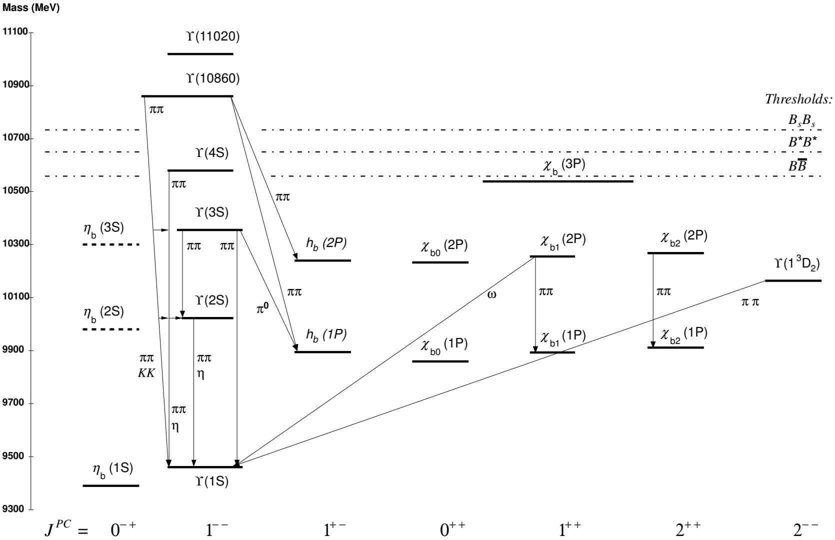

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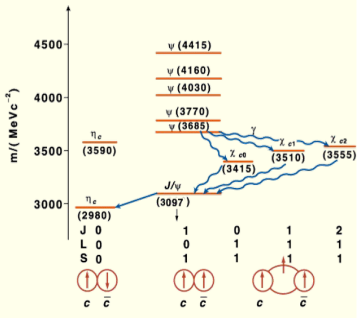

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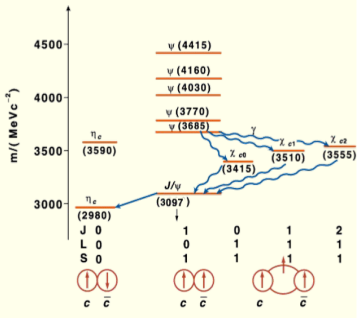
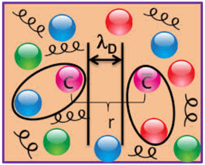


- Expected to melt in the QGP by Debye screeening

Matsui, Satz 1986



One probe, but different sources

Example: different ways to produce quarkonia in pp/A collisions

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- **Prompt** production:

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  Ex: $gg \to B\bar{B} \to \chi_c + X \to J/\psi + X$ **rejected**

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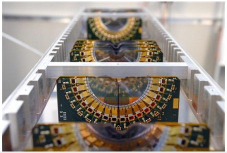

The study to separate prompt from non-prompt events is done thanks to a vertex detector

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- **Non-prompt** production:

  -with an intermediate b quark decay : $gg \to B\bar{B} \to J/\psi + X$ **accepted**;

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- **Direct** production:

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  -Excludes excited $\mathcal{Q}'$ decays : $gg \to \chi_c g \to J/\psi + \gamma + X$ **rejected**

  One needs to see the γ emitted by the χ_c.

One probe, but different sources

Example: different ways to produce quarkonia in pp/A collisions

- At high energy, the number of gluons able to produce a $\mathcal{Q}$ is very large
- Reasonable to consider only the production initiated by gluons
- BUT, for e.g. the $J/\psi(c\bar{c})$, there are several ways to produce it:
- **Prompt** production:

  -Excludes any intermediate b quark decay

  Ex: $gg \to B\bar{B} \to \chi_c + X \to J/\psi + X$ **rejected**

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  One needs to see the γ emitted by the χ_c.
- For the $\Upsilon(b\bar{b})$, only **direct** and **indirect**

Table of the branchings within the charmonium family

	J/ψ	χ_{c0}	χ_{c1}	h_c	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
η_c	1.7 ± 0.4	< 0.07	< 0.32	51 ± 6	< 0.32	< 25	0.34 ± 0.05
J/ψ	–	1.40 ± 0.05	34.3 ± 1.0	< 18	19.0 ± 0.5	< 1.4	63.4 ± 0.6
χ_{c0}		–	?	?	?	?	9.79 ± 0.20
χ_{c1}			–	?	?	?	9.75 ± 0.24
h_c				–	?	?	0.086 ± 0.013
χ_{c2}					–	?	9.52 ± 0.20
$\eta_c(2S)$						–	0.07 ± 0.05

Known values of or limits on the branching ratios for charmonium to charmonium decays [in per cent] (Source:PDG).

Table of the η_c branching

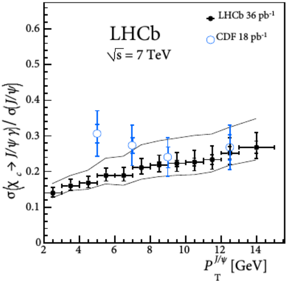
F.Yu, *et al.***arXiv:1901.09766**

	$\mathcal{B} \times 10^3$								
	$p\bar{p}$	$\phi\phi$	ϕK^+K^-	$\phi\pi^+\pi^-$	$\Lambda\overline{\Lambda}$	$\Xi^+\Xi^-$	$\Lambda(1520)\overline{\Lambda}(1520)$	$\eta_c\gamma$	$p\bar{p}\pi^+\pi^-$
η_c	1.52 ± 0.16	1.79 ± 0.20	2.9 ± 1.4	unknown	1.09 ± 0.24	0.90 ± 0.26	-	-	5.3 ± 1.8
J/ψ	2.12 ± 0.03	forbidden	0.83 ± 0.12	0.87 ± 0.09	1.89 ± 0.08	0.97 ± 0.08	unknown	17 ± 4	6.0 ± 0.5
χ_{c0}	0.22 ± 0.01	0.80 ± 0.07	0.97 ± 0.25	unknown	0.33 ± 0.02	0.48 ± 0.07	0.31 ± 0.12	forbidden	2.1 ± 0.7
h_c	< 0.15	forbidden	unknown	unknown	unknown	unknown	unknown	510 ± 60	unknown
χ_{c1}	0.076 ± 0.003	0.42 ± 0.05	0.41 ± 0.15	unknown	0.11 ± 0.01	0.08 ± 0.02	< 0.09	forbidden	0.50 ± 0.19
χ_{c2}	0.073 ± 0.003	1.06 ± 0.09	1.42 ± 0.29	unknown	0.18 ± 0.02	0.14 ± 0.03	0.46 ± 0.15	forbidden	1.32 ± 0.34
η_c'	0.07^*	unknown	unknown	unknown	unknown	unknown	unknown	forbidden	unknown
ψ'	0.29 ± 0.01	forbidden	0.07 ± 0.02	0.12 ± 0.03	0.38 ± 0.01	0.29 ± 0.01	unknown	3.4 ± 0.5	0.60 ± 0.04

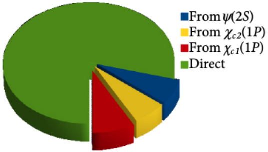
*Indirect determination

Feed downs from the excited states

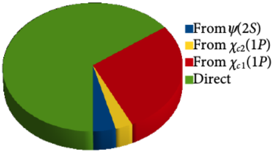
JPL, arXiv:1903.09185.



(a)



(b) Low P_T J/ψ



(c) High P_T J/ψ

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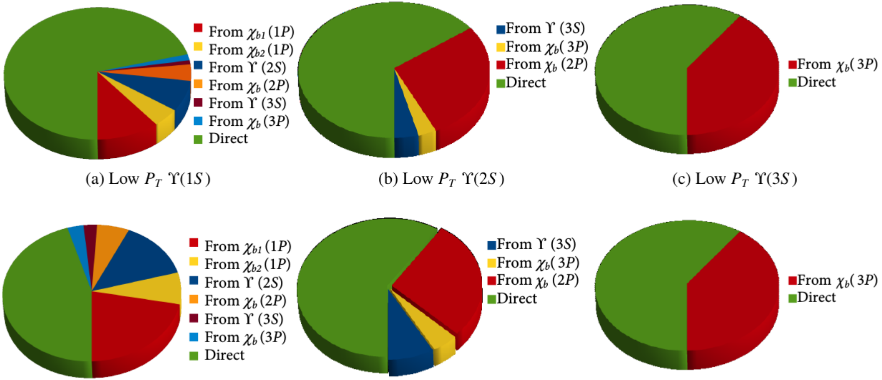

(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$

(d) High P_T $\Upsilon(1S)$ (e) High P_T $\Upsilon(2S)$ (f) High P_T $\Upsilon(3S)$

Part IV

Introducing quarkonium production

Approaches to (Inclusive) Quarkonium Production

See arXiv:1903.09185 and EPJC (2016) 76:107 for reviews

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  3. COLOUR OCTET MECHANISM (encapsulated in NRQCD): higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson; bleaching with semi-soft gluons ?

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3. Colour Octet Mechanism
   - one non-perturbative parameter per Fock State
   - expansion in v^2; series can be truncated
   - the phenomenology partly depends on this
   - HQSS relates some non-perturbative parameters to each others and to a specific quarkonium polarisation

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H. Fritzsch, PLB 67 (1977) 217; F. Halzen, PLB 69 (1977) 105

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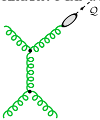

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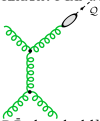

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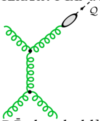

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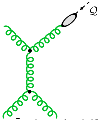

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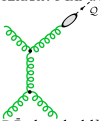

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- It can easily be checked by MCFM at NLO for instance `http://mcfm.fnal.gov/`
- Low predictive power, yet overshoots the data at large P_T; issues with the χ_c's

Basic pQCD approach: the Colour Singlet Model (CSM)

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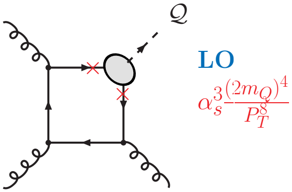

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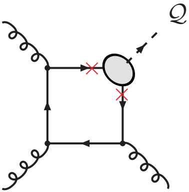

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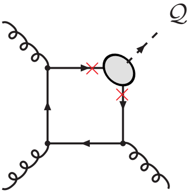

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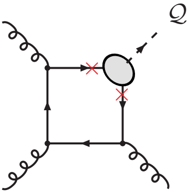

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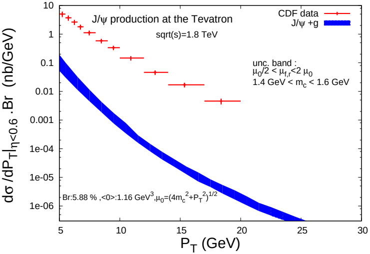

CDF, PRL 79:572 & 578,1997

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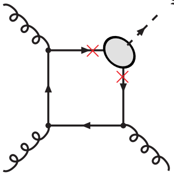

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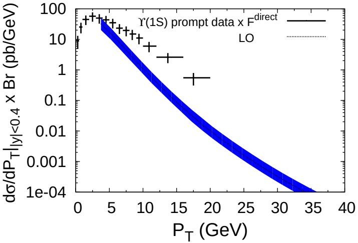

CDF, PRL 88:161802,2002

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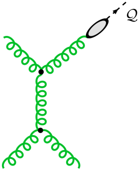

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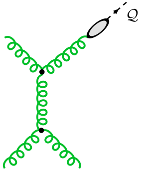

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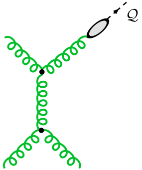

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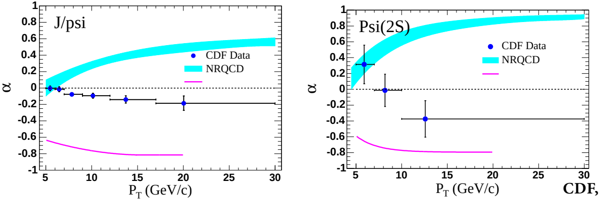

CDF, PRL 99: 132001, 2007

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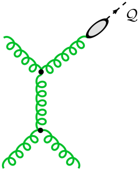

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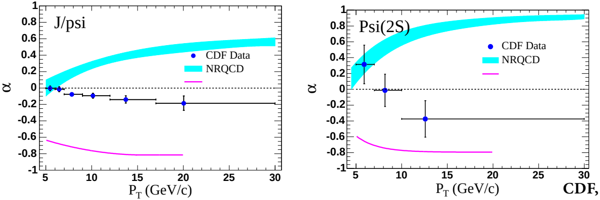

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✗ Cannot describe both the high P_T slope and the P_T-integrated cross section